CERAMIC FORMING BY ELECTROSTATIC ATOMIZATION

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Abstract

A concentrated alumina suspension was subjected to electrostatic atomization in the cone-jet mode. A point-like ground electrode was used to focus and print the spray on a substrate which was moved using a computer-controlled printing device. Several patterns were printed and alumina relic sizes were dramatically reduced with the increase in applied voltage. This work points to the development of a novel ceramic solid freeforming fabrication process.

Introduction

Layer manufacturing processes can be classed into five major categories which are:
(1) Liquid solidification where photosensitive resins are cured by UV light or laser, e.g. stereolithography.
(2) Melt deposition in which molten material layers solidify as it cools, e.g. fused deposition modelling.
(3) Powder sintering where layers of powder are fuse-bonded using a laser, e.g. selective laser sintering.
(4) Sheet lamination in which sheets of material are cut to shape, stacked and glued together, e.g. laminated object manufacturing.
(5) Ink-jet printing where powder layers are bonded using a jet of binder, or a suspension of the powder is jet printed directly.

Ink-jet printing has been very successfully applied to ceramic materials [1,2], where 30-60μm diameter nozzles are used to generate 60-120μm droplets (approximately twice the size of the nozzle diameter). Thus, droplet relics a few hundred micrometers in size can be expected [3]. In this paper, we show that computer-aided controlled deposition of much finer droplets produced by electrostatic atomization of a ceramic suspension can give a much smaller relic size and thus a novel ceramic freeforming technique has been uncovered.

A liquid flowing through a nozzle, kept at a high voltage, reference to a ground electrode, electrostatically atomizes, producing a spray [4]. Electrospraying in the cone-jet mode produces near-monodisperse droplets of a few micrometers in size [5] and can be used to process ceramic suspensions [6]. Nozzles used in electrostatic atomization can be several hundred micrometers in size, almost ten times bigger than those used in ink-jet printing. Ceramic suspensions usually contain a high level of solids and their viscosities can easily be >1000mPa s. These suspensions also contain volatile liquids. Thus, nozzle blockages are a problem and the ability to use coarser nozzles to generate relics, usually an order of magnitude finer compared with ink-jet printing, is a major advantage.

Experimental details

An alumina suspension, containing ~20 vol% of solids was prepared using a high energy bead mill. The details of materials used and the method of mixing has been discussed fully in our previous work [7]. Key properties of the suspension (density, viscosity, electrical conductivity, surface tension and relative permittivity) were measured and full details of these characterisation procedures are given in our previous work [8].

The electrostatic atomization equipment (**Figure 1a**) consists of a stainless steel nozzle (0.2 mm and 0.48 mm inner and outer diameter, respectively) held in an epoxy resin, 6mm below which a point-like ground electrode is held. Electrodes were connected to a 15kV high voltage power supply. The nozzle was connected to a perfusor syringe pump with silicone rubber tubing and the flow rate of the suspension to the needle was varied between 10^{-9} - 10^{-13} m^3s^{-1}.

The printing system (**Figure 1b**), is an x and y-axis stepper motor driven unit. The x and y tables are mounted directly on each other. The movement of the tables are controlled by sensors. The stepper drives provide mini-stepping technology and with a ball screw pitch of 5mm, allows a theoretical print resolution of 2.5 μm. The unit is controlled using a programmable motion-controller communicating directly with a PC. A perspex table, the top of which accommodates a frame for holding the substrate is mounted on the unit as shown in **Figure 1b**.

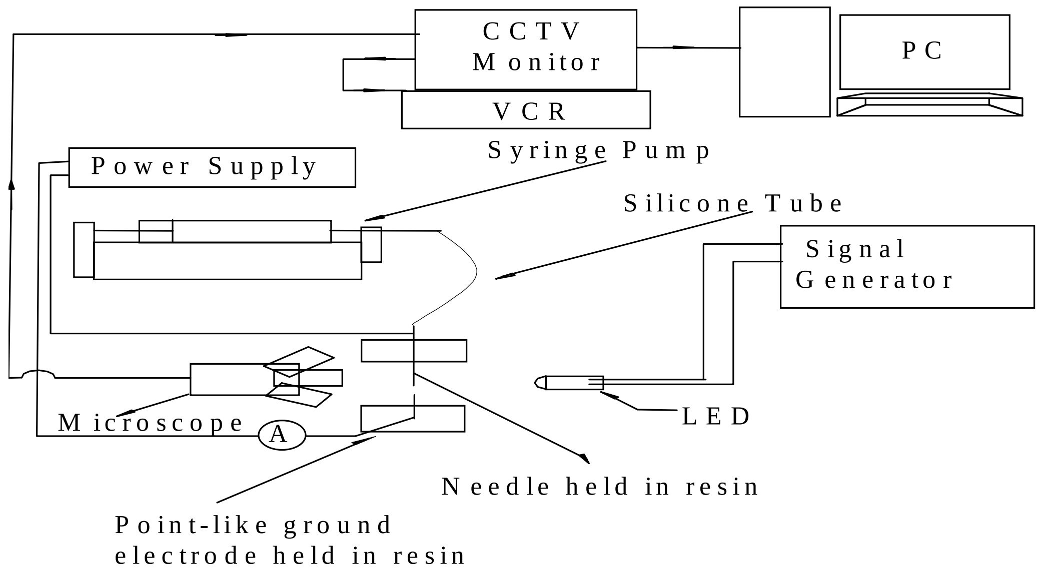

Figure 1a. The electrostatic atomization rig.

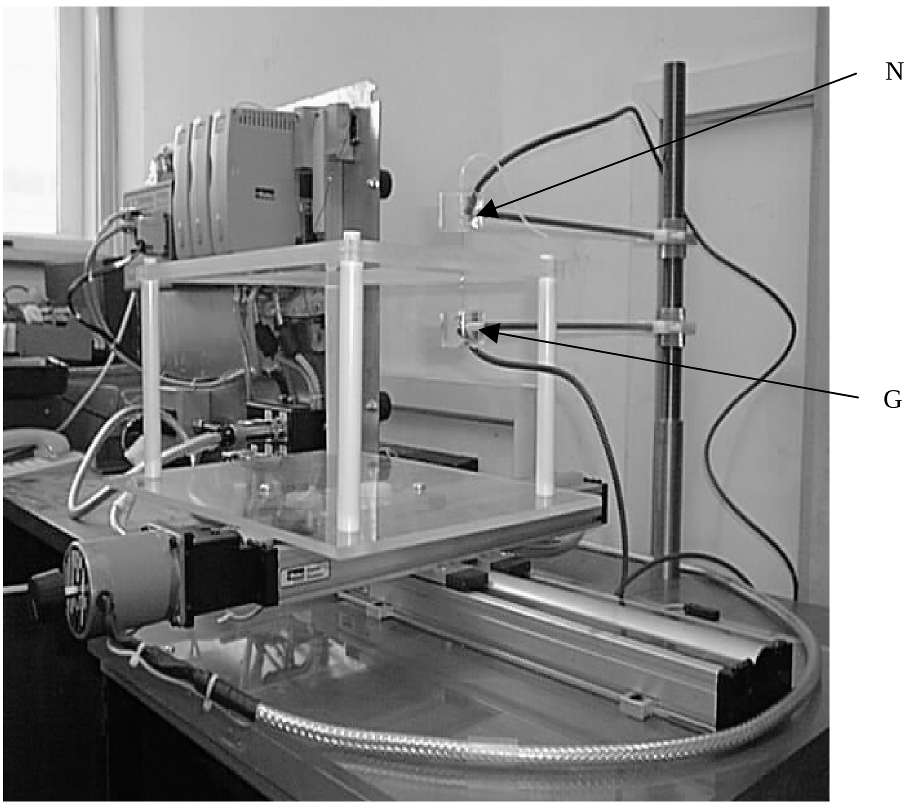

Figure 1b. The printing system with N and G denoting the nozzle and ground electrode, respectively.

Patterns were created using x and y co-ordinates and downloaded to the 2-axis controller using Motion Planner software. This allows the system to follow the path of the coordinates given, enabling printing. The nozzle and ground electrode were fitted firmly in place and kept in line with each other. The A4 size substrate which was an acetate sheet used in laser printers, was placed in the frame and held firmly between the nozzle and the ground electrode which was in contact with the substrate throughout printing. Suspension was pumped through the nozzle and a voltage was applied between the nozzle and ground electrode.

The flow rate and applied voltage were adjusted to obtain the stable cone-jet mode of electrostatic atomization. Subsequently, the flow rate was kept constant at $1.67\times10^{-9}\ m^3s^{-1}$ but the applied voltage was varied between 8kV and 10kV and printing of the word **CERAMIC** was performed at different voltages. The movement of the droplets from the nozzle to the ground electrode was observed using a high speed Kodak EktaPro EM Motion Analyser Model-1012 camera. The droplet relics in the prints were studied soon after deposition by optical microscopy. Relic sizes were measured using Image-Pro Plus software. Macro-photographs of the prints were also taken.

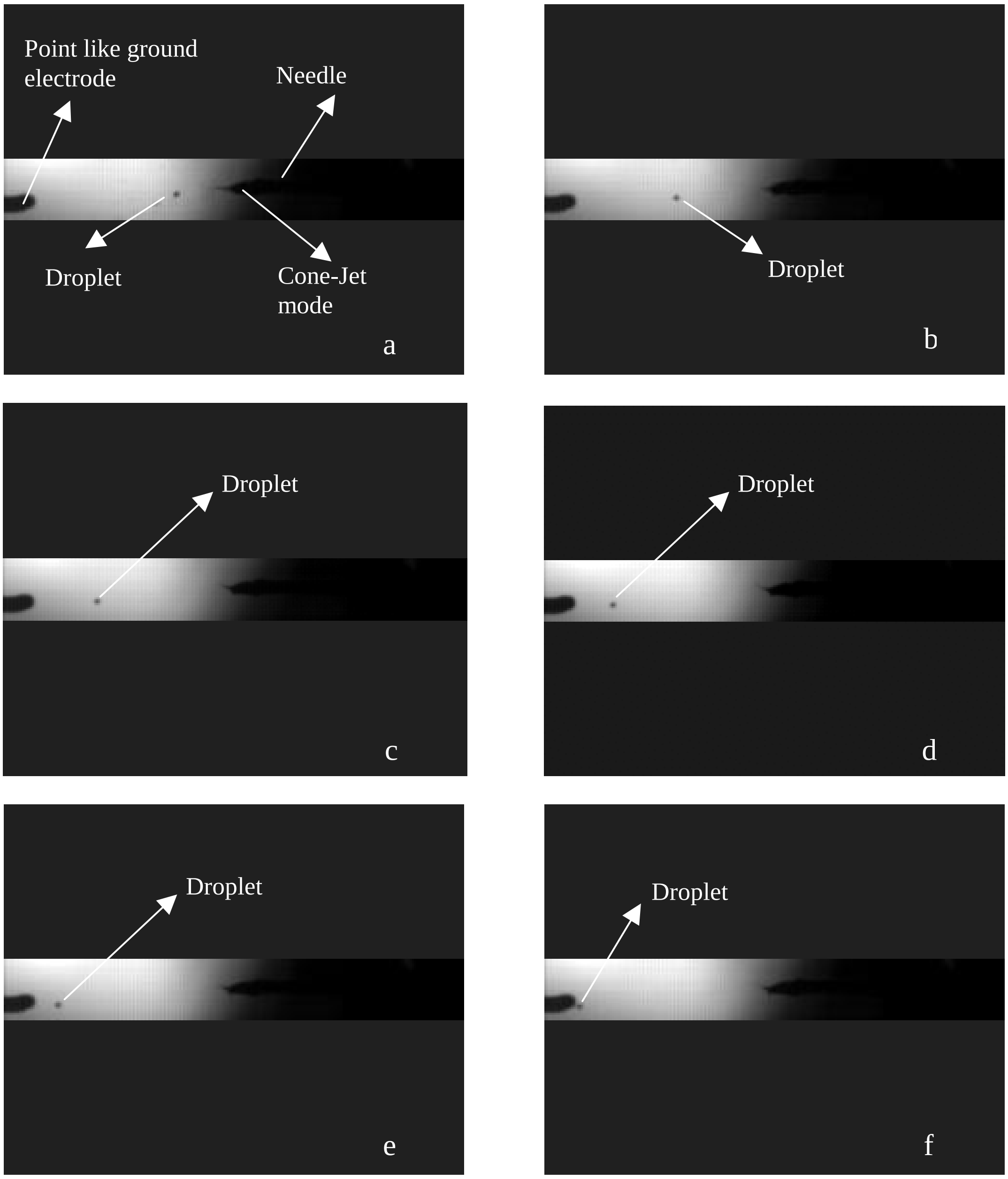

Figure 2. Sequence a to f shows a droplet of the suspension moving to the ground electrode.

Results and Discussion

The suspension contained 21 vol% of alumina as determined by loss-on-ignition results and its properties are given in **Table 1.**

Table 1. Composition and properties of the alumina suspension subjected to electrostatic atomization.

Alumina		Ethanol	EFKA 401	Density	Viscosity	Surface tension	Electrical conductivity	Relative permittivity
Wt%	*vol%*	*wt%*	*wt%*	*kgm^{-3}*	*mPa s*	*mNm^{-1}*	*mSm^{-1}*	
56.5	20.6	43.0	0.5	1413	1420	64	0.043	54

The viscous dimensionless parameter (δ_m) is defined as [9]:

$$\delta_m = \sqrt[3]{\frac{\rho \varepsilon_0 \gamma^2}{K \eta^3}} \tag{1}$$

where ρ is the density, γ is the surface tension, K is the electrical conductivity and η is the viscosity. Using the values in **Table 1**, for the alumina suspension $\delta_m \leq 1$ and this helps to obtain the stable cone-jet mode of electrostatic atomization. **Figure 2** shows droplets guided towards the ground electrode. The use of a ring-shaped ground electrode in previous work with ceramic suspensions [6], allowed the droplets to spread. In stark contrast, the use of a point-like ground electrode helps to focus the droplets.

For $\delta_m \leq 1$, the jet diameter (d_j) can be estimated by [9]:

$$d_j \approx \sqrt[3]{\frac{(\beta - 1)^{\frac{1}{2}} Q \varepsilon_0}{K}} \tag{2}$$

where β is the relative permittivity. From **Table 1**, at the flow rate (Q) of 1.67×10^{-9} $m^3 s^{-1}$ used in this work, equation (2) gives d_j ~14μm for the suspension. The measured jet diameter was 17μm at 8kV and decreased to 6μm at 10kV. The discrepancy is because the jet diameter is affected by the viscosity of the suspension [10] and the applied voltage [11], both not directly taken into account in equation (2).

High quality printing was achieved and examples are shown in **Figure 3**. To accommodate some characters (e.g. the E in **Figure 3**) some over-printing had to be performed. In the case of line printing without overprinting, the relic sizes at an applied voltage was found to be remarkably consistent in each character. At 8kV, the relic sizes were in the range 350-400μm but there was a significant decrease in the relic size distribution on increasing the applied voltage to 10kV at which the measured relic sizes were between 30-60μm. However, as the applied voltage was increased focussing the spray was increasingly difficult and more scatter of relics is clearly observed (**Figure 3b)**. Furthermore, the substrate was not optimized to minimise spreading and this can be improved significantly to further reduce the relic sizes.

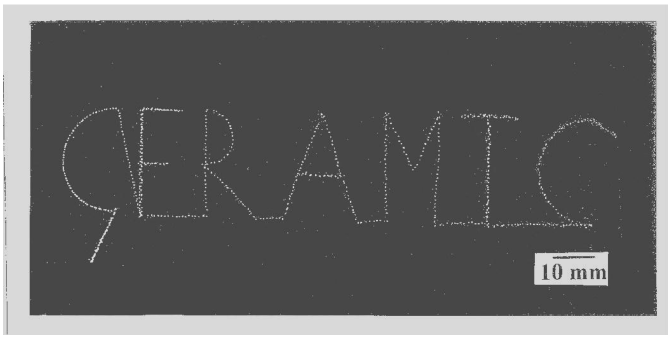

Figure 3a. Printing performed at an applied voltage of 8kV.

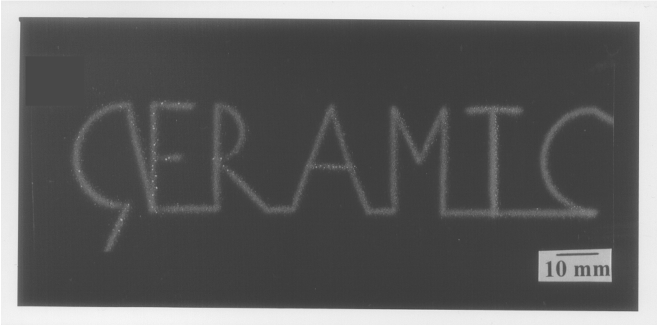

Figure 3b. Printing performed at an applied voltage of 9kV.

Figure 3c. Printing performed at an applied voltage of 10kV

Conclusions

This work pioneers a step change in reprographic techniques and this method is currently being developed into a ceramic solid freeforming method. This simple and economical method clearly allows the production of ceramic tracks <50μm in thickness and also demonstrates further scope for the controlled deposition of very fine droplets of ceramic suspension with relics of the order of a few micrometers. The improved resolution allows the microfabrication of small, complex components with high microstructural integrity.

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